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NOLTR 62-197

THE SHOCK-TO-DETONATION TRANSITION IN SOLID EXPLOSIVES

13 NOVEMBER 1962

NOL

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 62-197

THE SHOCK-TO-DETONATION TRANSITION IN SOLID EXPLOSIVES

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ABSTRACT: Experiments on the initiation of detonation in cast and pressed explosives (TNT and various cyclotols), subjected to plane shocks introduced at a plane surface, are presented and discussed. Shock amplitudes ranging from 28 to 140 kilobars in the explosive were generated by using plane wave lenses with various combinations of donor explosive and barrier composition and geometry. The shock velocity was obtained in each sample as a function of distance of travel into the wedge-shaped specimen from distance-time records obtained with a smear camera. The resulting curves for cast explosives are found to be quite different from those for pressed explosives. Furthermore, cast TNT exhibited a result anomalous to the other cast charges. The observations are interpreted as showing evidence that "hot-spots" must be present behind the shock to explain the rapidity with which the detonation is established. Sources of hot-spot formation are suggested. The results obtained at the lower shock amplitudes when compared to results on the NOL gap test lend support to the idea that peak pressure and pressure history in the shocked elements of explosive are far more important than wave shape in determining the time for transition to detonation.

PUBLISHED APRIL 1963

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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NOLTR 62-197 13 November 1962

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This report describes recent NOL experimental work and thinking concerning the phenomenon of initiation of detonation in an explosive subjected to a plane shock of known peak amplitude. The necessary information on shock amplitude is obtained by means of direct measurement of shock velocity in the experiment. These results taken in conjunction with related experiments and theoretical work on the transition from shock to detonation are believed to contribute substantially to our understanding of how explosives are initiated. This understanding is of utmost importance in defining the sensitivity of explosive and propellant materials, and in defining the variables which are important to characterizing sensitivity. The ultimate objective of work along these lines is the establishment of a basis for safety in handling and reliability in the use of military ordnance.

This report was presented as a discussion paper at a Detonation Phenomena session of the Ninth Symposium (International) on Combustion held at Cornell University on August 27 - September 1, 1962, and sponsored by the Combustion Institute. It will eventually be published as a contribution to the Proceedings of that Symposium.

The work was performed under NOL Task 260, Project LACE.

A previous NOL report to which this work is related appeared as NAVORD Report 5710, confidential.

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Captain, USN
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By direction

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INTRODUCTION

It may be of historical interest to note that many years ago Cornell University was the scene of another discussion on the problems of shock-to-detonation transition. In 1945 a small group of scientists from the OSRD, the National Research Council of Canada, the Army, and the Navy met here to exchange ideas concerning detonation in explosives. G. Hertzberg (1) described to that group some interesting smear-camera records he had obtained concerning the initiation of detonation in solid and liquid explosives. At the same meeting he described a card-gap test which was probably the first of many to follow. E. Boggs (2) also presented a number of important, and at that time perplexing, experimental observations on the transition from shock to detonation. The work discussed in that meeting, and much of the work that followed, suffered for lack of quantitative description of the forces and energies present in the incoming shock which cause a detonation to form.

After a lapse of over ten years, work began to be reported in the open literature which described in quantitative terms the build-up to detonation from shocks of known pressure amplitudes (3-7). The list of papers has grown rapidly in more recent years (8-15). In the majority of these papers the build-up to detonation has been attributed to an initiation of chemical reaction by either a uniform or a localized temperature rise associated with the adiabatic compression, followed by growth determined by the continued speed-up of the reaction once begun. An alternate hypothesis which postulates the development of high thermal conductivity behind the shock leading to a heat pulse has also appeared (16-17). The latter hypothesis makes no clear distinction between the behavior of liquids and polycrystalline solids. The former, more prevalent, viewpoint supplies a framework for explaining differences in behavior: (a) between solids and liquids, (b) between solids formed by different techniques (such as by casting or by pressing), (c) due to geometric configurations of the medium under study, and (d) due to spatial and temporal distribution of pressure and flow. The transition to detonation in a liquid explosive, when a plane step shock is induced in it, appears to be the simplest to explain in its physical aspects (8, 19-20). Here the temperature rise in a homogeneous compression seems sufficient to account for the build-up to detonation. The meager evidence from experiments on single crystals, carried out in such a way that rarefaction effects may be considered negligible, are in accord with this model (9).

The response of polycrystalline solid explosives to the entering shock is not as clear as in the case of liquid explosives. Solid explosives are formed into a mass which contains numerous crystal entities, and both macroscopic and microscopic voids. When initiated by plane shocks of low shock amplitude, the dependence of build-up time on crystal size and void content makes it fairly evident that the low temperature rise calculated for a homogeneous compression cannot account for the observed transition. Thus a hot-spot mechanism of the type suggested by Bowden and others (21-24) is required. The confirmation of early work by Winning (7) and Marlow (6), who reported that induced shocks with pressures as low as 20 kilobars would cause transition-to-detonation, has established important support of a mechanism centered around a relatively small number of initiation sites. Studies to show how a detonation develops when both the physical state of the explosive and the shock amplitude are varied, are beginning to lead to a better understanding of the nature, magnitude and behavior of the initiation sites.

The shock-to-detonation transition has been studied at NOL by the use of a plane-wave system arranged in such a way as to make it possible to follow continuously the wave front within the shocked sample (3, 4). The experiments to be described have made it possible simultaneously to establish the initial pressure in the shock and to observe the growth-to-detonation as it develops. The observations are made on a wedge-shaped test sample, the wedge permitting observations without grossly affecting the one-dimensional flow in the region of interest. This is equivalent to the observation of growth within an explosive charge of much larger dimensions. Thus, the results appear to agree reasonably well with shock-initiation work on long cylinders of cross-sectional area comparable to the area of the face of the test wedge, provided: (a) the observations in the cylinder are made in the region of its axis (not on its exterior surface), and (b) the pressure-time histories of the entering shock are similar. The results of these experiments are in accord with the explanation that growth-to-detonation in polycrystalline solids is the result of pressure build-up from temperature-triggered chemical reaction spreading from localized sites.

EXPERIMENTAL

A typical set-up for generating 20-to 180-kilobar, plane shocks in the test specimen is illustrated in Figure 1. In this example the 11-cm diameter plane-wave generator developed a detonation wave that was flat to ± 0.3 mm over a diameter of 9 cm. A slab of explosive, 12.5 cm x 12.5 cm x 2.5 cm was placed between the generator and a 20-cm diameter disc of inert barrier, or shock attenuator. A sample of the test explosive,

in the form of a 25° wedge (apex angle 90°) was then placed on the opposite face of the attenuator. (A thin film of silicone grease was generally placed between the attenuator and the test wedge to minimize the possibility of accidentally causing a hot-spot by a small amount of entrapped air in the region.) In general the test wedges had faces 3.2 cm by 3.2 cm, and therefore were 1.4 cm high. For the less sensitive explosives, or where very low-amplitude shocks were to be used, larger wedges were employed: faces 5 cm by 5 cm, and by changing to a 30° angle, were 2.6 cm high.

The different pressure levels in the test explosive wedge were obtained by varying the different components of the shock-generating system. Thus, the slab of explosive, between the plane-wave generator and the inert shock attenuator, was either cast Composition B, Baratol, or TNT; in addition, the thickness of this slab was increased to as much as 5 cm, as the need warranted. The attenuator was either solid brass, aluminum, or Plexiglas, or was made from 1-cm thicknesses of such materials in various laminated configurations, to produced the desired shock pressures.

The phase velocity of shock arrival along the wedge free surface was determined with a smear camera having a writing speed of 3.8 mm/microsecond. The arrival of the wave was recorded by the camera by using an aluminized Mylar film on the surface of the specimen, and reflecting light from an electrically-exploded wire confined in a glass capillary. When the wave reached any point on the surface, the reflection from the Mylar mirror was abruptly reduced, as shown in Figure 2, permitting precise determination of time vs distance of penetration of the shock into the wedge. Velocity of shock propagation was then obtained by graphical differentiation. The wedge angle was chosen to be as small as possible consistent with the desired height, so that rarefactions from the region previously shocked would not penetrate into the region behind the yet-unshocked portion of the wedge in time to effect the desired observations.

For each experimental arrangement the initial free-surface velocity of the attenuator, without the explosive sample, was determined by direct measurement in an identical lens-donor-attenuator system. Similar preliminary experiments determined that, at the center of the plate, over a diameter of 5 cm, or more, the time-of-arrival of the shock was simultaneous to within 30 nanoseconds, while the free-surface velocity was constant to within ± 2%. The particle velocity in the attenuator, at the metal-specimen interface, is then given by the usual assumption that it was one-half the measured initial free-surface velocity. The shock Hugoniots for Plexiglas and for the Naval brass used

in these experiments were obtained by direct measurement of shock and free-surface velocity by the methods described by Rice et al (24), and by Coleburn (25). The Hugoniot for 24ST aluminum was taken from the report by Rice (24).

INFORMATION OBTAINED

The explosives studied and their pertinent properties are listed in Table I. The observed time-of-arrival of the shock disturbance at the wedge free surface was converted to a velocity-distance (U-s) curve within the wedge, by careful slope measurement of the smear-camera record, assuming plane-wave propagation inside the wedge. As shown below, the value of the observed shock velocity at zero wedge thickness was used with the Hugoniot data for the shock attenuator, to determine the initial pressure in the explosive. Hugoniots for the unreacted explosives were then constructed from these data, assuming that negligible chemical reaction had occurred at this zero wedge thickness during passage of the shock. Shock velocities at low pressure ($p \sim 2KB$) were established from measurements made on the same explosives, using a simple aquarium method for shock transit-time observations (26).

The shock Hugoniots for both the inert barriers and the non-reacting explosives are conveniently expressed by relating shock velocity (U) to particle velocity (u) in the simple form:

$$U=a+bu+cu^2, \qquad 1)$$

where a, b, and c are constants. When this equation is applied to the experimental data by the method of least squares, the value of the constant, c, is often so small, that in the region of interest, the U-u relation can generally be considered linear to acceptable accuracy. The values of a, b, and c in this equation are listed in Table II for a number of materials used in our work. Pressure, density, and energy jumps across the shock front are derived by the well-known hydrodynamic relations for a shock (assuming initial pressure negligible):

$$p=\rho_o U u, \qquad 2)$$

$$\rho=\rho_o U/(U-u), \qquad 3)$$

$$E-E_o=p(v_o-v)/2=u^2/2, \qquad 4)$$

where p is pressure, ρ is density, E is specific energy and v is specific volume (reciprocal of ρ). Subscript "o" refers to the unshocked state. The particle velocity in the non-reacting explosive was determined by boundary-value matching of p and u, as illustrated in Figure 3, using the calibrated values of

particle velocity and pressure in the barrier (at the barrier, test-explosive interface) and the observed shock velocity in the test explosive (at the same interface). In the Figure, subscript "e" refers to states within the shocked explosive; subscript "m" refers to states within the shocked metal barrier. In applying this method, the p-u curve for the reflected rarefaction (or shock) wave within the barrier (in this illustration, brass) is approximated by the reflection of the shock p-u curve for the barrier, about the line: u equal to 1/2 the free surface velocity for the barrier in the given experiment. Since the pressure and the particle velocity across the interface must be continuous, the desired solution is the intersection of this rarefaction line, with the straight line for the explosive passing through the origin and having a slope

$$p/u = (\rho_o U)_e, \qquad 5)$$

where U is the measured shock velocity in the test wedge of explosive, at the barrier-wedge interface. In spite of the approximation involved, this method is a substantial improvement over the linearized impedance equation assumption often made, and previously used in this Laboratory (3). The latter method leads to a larger systematic error in the pressure and particle velocity than the present approach.

RESULTS

The experimental observations may be conveniently shown as graphs of shock velocity in the explosive sample as a function of distance traveled from the metal interface. Figures 4 and 5 are typical of the results found at NOL. In Figure 4, the results for the three cast cyclotols are shown for three initial shock amplitudes using brass attenuators. The first point to be noted is that the initial wave velocity increases as the brass plate thickness decreases. The initial values for the two Composition B types are the same for a given brass thickness. These velocities were converted to the pressures shown in Figure 4 by the procedure previously described. The second feature of the curves is that the distance to build-up-to-detonation is a function of the initial pressure. Composition B-3 shows a shorter transition distance than Composition B at each pressure level. The difference most probably is due to an RDX particle-size effect. The curves of Figure 4 are typical of the largest majority of records obtained in this Laboratory on over a hundred trials with a number of cast and plastic-bonded explosives at bulk densities in excess of 97% of theoretical maximum.

TNT, when cast, exhibits a somewhat different shock propagation history. For initial pressures in the explosive below 100 kilobars our records consistently show evidence of what

appears to be a levelling off of velocity in the neighborhood of 5.3 mm per microsecond, followed by a second rise, to normal detonation velocity, Figure 5a. This type of observation has appeared too frequently for us to attribute it to reading error. J. M. Majowicz (3) first observed this initial step, but failed to see the later transition- to-detonation because his wedge was only 14 mm in height. The final transition is seen to occur at greater distances in the pressure range shown in Figure 5a. When the initial shock in the cast TNT exceeded 130 kilobars, the initial wave velocity exceeded this intermediate, plateau value and only one transition was observed, with a considerably shortened distance to detonation. For pressed TNT, the results for low initial shock pressure show new features, Figure 5b. The observed initial shock velocity is out of line when compared with the results from cast TNT, being too high for a non-reactive shock. Furthermore, the transition-to-detonation occurs in a distance considerably shorter than in the case of cast TNT charges shocked by the same shock generator system. One may note that one of the curves in Figure 5b involves a pressed charge at a density higher than that of the cast TNT, yet the growth distance to detonation is still only 4 mm as compared to 15 to 20 mm for the cast charges shocked in a similar manner. It is therefore quite clear that charge porosity per se is insufficient to describe the effect of physical state on the transition history. The effect of pressing, shown here for TNT, in shortening the transition distance is also present in the cyclotols and in other explosives. We may cite Composition B as an example: with a 1-inch brass barrier (initial p_e=77 kilobars) pressed Composition B reached full detonation velocity in less than 2 mm, compared to 4 mm for the cast explosive.

The "overshoot" shown in the velocity-distance curve of pressed TNT, Figure 5b, requires comment. In pressed explosives our camera records consistently have shown this irregularity, which we have interpreted as a transient rise to velocities in excess of the normal detonation rate. In some records the velocities appear to be as much as 50% over normal, but more frequently, as shown in Figure 5b, the excess is about 20 - 30%. Such overshoots are entirely possible, we believe, on hydrodynamic grounds, depending on the nature of the reaction-rate profile behind the shock front. On the other hand the distance over which excess velocity has been observed in our records is small, of the order of 1-3 mm. While reading errors, made during measurements of phenomena rapidly changing over such small distances, are aggravated by the mathematical process of differentiation, careful examination of the photographs indicate that the records definitely exhibit such super-velocities. We believe, therefore, that the photographic evidence of the overshoots is beyond reading error, although the magnitudes of the overshoots cannot be precisely determined. Campbell, et al (9), have also

studied pressed charges. They have been quite emphatic that no overshoot had been detected in any of their experiments on pressed solids. We admit that there is room here for honest differences, and these may be due to differences in the two sets of experiments. More refinement of the experiments are needed to settle the question.

The transition distance vs initial shock amplitude within the explosive has now been determined for cast Composition B-3, over the range 30 - 130 kilobars. It has been found that a straight line very nearly fits the results if one plots the reciprocal of the distance against the initial pressure, as shown in Figure 6. This line extrapolates to an infinite distance at p_ϕ=28 kilobars. This can be interpreted as an indication of the threshold pressure for initiating this explosive with the given shock generator. A cursory examination has been made of the rate of pressure decay behind the shock in the shock generator system used to obtain the data of Figure 6. Our best estimate is that the pressure will fall to about 60% of peak in a time of 2 microseconds after passage of the shock into the explosive, in the absence of chemical reaction. This decay rate is comparable to that estimated to occur in the NOL gap test (12). When Composition B-3 was tested in that gap experiment, the 50% point for detonation was found to require an initial peak pressure in the explosive of 20 kilobars. The closeness of the threshold shock pressures in the two experiments for the same explosive may be used to infer that the long cylinders will, near the sensitivity limit, show the same uniform initial velocity as we have found in the wedges at very nearly the same pressure level. The velocity would be near acoustic because at pressures in the neighborhood of 20 kilobars the shock wave velocity is near to the limiting acoustic value. Cachia and Whitbread (5) have actually observed this initial "constant" velocity with ionization probes embedded in cylindrical charges at somewhat higher pressure levels (U=4 mm/microsecond). The 50% gap experiment has shown a very sharp cut-off between "go" and "no-go" in Composition B. It now appears that the range between practically 0% probability of detonation build-up and practically 100% probability is about 1 to 2 kilobars in the donor shock. We could interpret this result to mean that in the constant velocity region the shock pressure is actually increasing by about this amount in the cases where a detonation is established.

DISCUSSION

The clarification of the nature of the growth-to-detonation from a mechanical shock has required that quantitative measurements of the initial shock pressure be established. Since the first work at NOL we have mapped out (non-reactive) shock Hugoniots for a number of solid explosives; two are presented

here. Our work has shown that both time and distance for growth-to-detonation is monotonely related to this initial shock amplitude. In 1956 an ad hoc theory was presented in a note by one of us (27) to relate the growth process to shock and reaction variables. It was pointed out in that note that the history of the build-up would probably depend not only on the initial shock amplitude but also on the nature of the rarefactions behind the initial shock. A subsequent paper by Majowicz and Jacobs (3) concluded that the build-up in experiments such as those presented here, must have involved a substantial induction period before any chemical reaction occurred, because the observed shock velocity was initially constant, insofar as we could determine. Our present position has changed in regard to this delay mechanism. It is now clear to us that our initial shock was followed by a rather steep pressure decay. In the presence of this rarefaction, the velocity of the leading shock in the explosive should have fallen by a measureable amount if it had not been supported by energy contributions from reactions which must have occurred shortly after passage of the shock. The absence of such a velocity decay indicates that the rate of the reaction closely behind the wave must be increasing as the shock progresses, so that ultimately, the reaction rate, increasing non-linearly, causes the shock to build-up very rapidly to a detonation.

There now have been reported a number of related studies by several groups to describe in quantitative terms, the growth-to-detonation in solids. Through these studies it is apparent that a unified picture is emerging. In discussing the problem we find important support in the work of Campbell et al (9), who used plane shocks as we did, but employed donor charges which were considerably larger, thus leading to a much slower decay of pressure behind the incident shock. Brown and Whitbread (15), who studied initiation by the impact of disks made of several materials, showed quite clearly that the threshold for initiation depends on both the amplitude and duration of the initial shock within the explosive but not on the properties of the disk. Favier and Fauquignon (14) have also shown a dependence of the build-up distance on the pressure induced in the explosive irrespective of the attenuator composition. Similar findings have been reported by Sultanoff and Boyle (10) for shocks through various attenuating media including air, and for shocks induced by cylinder impact. Jaffe, Beauregard and Amster (12) have established the relation between barrier thickness and shock peak pressure in a controlled gap-test experiment and have thereby established thresholds for initiation where the duration of the incident shock is somewhat longer than that of Brown and Whitbread.

If we confine our attention to cast and plastic-bonded explosives, the conclusion reached by Cachia and Whitbread (5) and by Campbell, Davis, Ramsay, Travis (9) for build-up to detonation is, with minor modifications, the interpretation which we find acceptable. This may be stated as follows. The incident shock initiates a small amount of chemical reaction (in localized regions) with essentially no delay. The growth depends on the pressure effect due to the initial shock plus the pressure contribution due to the reaction. If the net pressure behind the wave increases, the leading shock will grow to a detonation. If it decreases the detonation will fail. The first point of complete reaction will depend on the reaction-time history experienced by the explosive layers after the shock has passed. If reaction in regions behind the shock are slowed down or stopped by adiabatic expansion or heat conduction, the detonation wave will probably form at or near the shock front, if it is formed at all. The extent of initial reaction and its subsequent growth in a given region will be strongly dependent on the shock amplitude entering that region.

Before exploring the mechanism further, we would like to point out a few facts and their implication concerning shock initiation of detonation near threshold pressures. It is now quite clear that detonations can be initiated in solid explosives by shocks with peak pressures between 20 and 40 kilobars, in cylindrical charges of 1-to 2-inch diameter or in comparable square charges (6, 7, 10, 12). By comparison, liquid nitromethane requires 86 kilobars, liquid TNT about 125 kilobars, and Dithekite 13 (HNO_3/nitrobenzene/H_2O;63/24/13) about 85 kilobars (8). In these low density liquids, the average temperature rise at these pressures, in the neighborhood of 800 to 100 °C, appears quite adequate to account for transition to detonation by an initiation process involving homogeneous reaction kinetics. The hydrodynamic calculations made by Hubbard and Johnson (18), Boyer (19), and Enig (20), clearly show a direct correspondence between what is observed experimentally and what is predicted from computer runs. In particular the rapid growth to a detonation behind the leading shock, the overshoot in velocity and pressure when this detonation overtakes the leading shock, and the subsequent decay to normal detonation, appear in both the experiments and in the computations. It is less clear that the temperature rise associated with a homogeneous compression can be sufficient to initiate reaction in solids at pressures of 80 kilobars, and at 20-30 kilobars such a possibility is out of the question. At 80 kilobars the Hugoniot energy jump given by equation 4 is 122 calories per gram for Composition B. If we assume that all of this energy is thermal and the specific heat is as low as 0.35 cal/g/deg the temperature rise would be 350°C on the average. At 30 kilobars the Hugoniot energy is only 28 cal/gm and the

average temperature rise using the above assumptions is 79°C. There is ample opportunity to consider the localizing of energy in microscopic regions (but large relative to molecular dimensions) within the solids under compression. Many workers following Bowden have noted the existence of small voids in solids, and have accepted the simple hypothesis that gas in such voids would get sufficiently hot under shock compression to supply the needed initiation temperature rise. This argument was tested by Cachia and Whitbread by comparing the 50% gaps for an explosive containing in its voids, various gases or a vacuum (5). The same 50% point was found in every case. Is it not possible that the void act in other ways? We think the answer is yes.

A few of the possible ways for localizing energy are the following:

a. Micro-roughness of the shock and shock-wave interaction (Campbell).

b. Elastic-plastic changes behind the shock front with localized shear or fracture.

c. Discontinuity of flow near voids leading to shear.

d. Discontinuity of flow at grain boundaries.

e. Spalling or spray into voids. (Johannson).

f. Phase change under shock loading.

g. Defects in the crystallities.

We do not have evidence to support unambiguously any of the above as the mechanisms. Our thinking has strongly leaned to shock-produced micro-shear or micro-fracture at or near voids, as the path by which the explosive is locally ignited, but we do not yet know precisely how to characterize these variables.

In the paper by Campbell on initiation of solids (9), evidence is cited to the effect that the explosive near the entering boundary reacts to only a small extent, transmits its excess pressure, and then apparently stops reacting. They state, on the basis of these experiments, that the explosive in that region not only fails to react to completion but also will not sustain further reaction when subjected to a second shock (as from the region where detonation finally is established). This argument is plausible, we believe, for some solid explosives in the wedge type experiment used by Campbell and by us. Two bits of information will be used to discuss this point. First,

Boyer (28) has used a model to compute the transition to detonation in solid explosives in which two mechanisms for reaction are assumed to proceed simultaneously. One is an ignition reaction based on first order homogeneous reaction kinetics; the second is a surface burning reaction in which the Arrhenius terms contained in the equation are the same as in the ignition reaction. An arbitrary limit of 1% of the total mass is allowed to react according to the ignition mechanism. The computed result showed a shock velocity vs distance curve very similar to those shown in Figure 4. The result also showed reaction to first go to completion at points in the explosive which were near the accelerating shock front. No basis is given for limiting the amount of material reacted by the ignition reaction to 1%. It is possible, however, that heat transfer from the reacted sites could, in fact, cause a limitation of reaction to this order of magnitude provided that the initial shock were not too strong. If it is assumed that localized reaction can quench after a very short time an explanation must still be found to account for failure to re-ignite and propagate a detonation backward after detonation is established in the forward direction. The following observation on detonation failure in preshocked solid explosives seem pertinent to this problem.

It has been established by repeated experiments in our Laboratory, that a steady-state detonation in a sheet of EL 506C[1] between 0.05 and 0.24 inches in thickness, can be quenched if the detonation encounters a region in the explosive which is being compressed to a high density by a second shock wave having a peak pressure between about 10 and 20 kilobars. In one series of experiments using the set-up of Figure 7, the explosive in two parallel layers separated by a plastic gap were initiated simultaneously at opposite ends. As both detonations propagated, the bow shock behind the detonations moved toward the alternate layer of explosive. Each layer of explosive was thus compressed by a shock from the alternate layer of explosive. When a detonation reached the preshocked zone it was seen to fail very quickly in smear camera records. Undetonated explosive could be picked up from the floor of the test chamber[2]. Other explosives have shown similar quenchout, e.g. cast HMX/TNT, HMX/Plastic. It is very likely that the shocked explosive reacted to some small degree

1. EL-506C is a pliable, sheet explosive, manufactured by E. I. duPont Co., containing approximately 70% PETN, and 30% inert material.
2. Johannson (31) has described experiments on dynamites in which air shocks, leading a detonation, could cause the detonation to fail.

because of the first shock, but then, not only was this reaction quenched in the manner suggested by Campbell, but also the explosive in this shocked, compressed state was unable to propagate a detonation already established in the unshocked region. These observations lead us to conclude that the hypothesis of Campbell can be valid under appropriate conditions. In the case of long cylinders shocked from one end, the retonation can be explained by the fact that rarefactions behind the growing shock (originating mainly at the cylinder sides), will return the explosive to a condition where it is again receptive to a build-up to detonation by a shock originating at the region where detonation is established. Some very interesting experiments described by Clay, et al (29) in which a shock in Composition B is found to grow to a detonation after passage through a preshocked zone also may find explanation in the observation of preshock quenching.

SUMMARY

We have examined the growth-to-detonation from mechanical shock for TNT and 3 cyclotols. Both cast and pressed charges have been studied. Experiments have been conducted over a pressure range from 30 to 120 kilobars. In the cast charges the initial wave in the shocked specimen has the character of a non-reactive shock. The initial wave velocities in these charges have been used to compute the peak pressures behind these initial shocks. The build-up to detonation has been found to be sensitive to the RDX particle size in two cyclotols of very similar composition and density. The build-up to detonation has further been found to occur more rapidly in pressed charges than in cast charges of the same composition and density. These observations lead us to conclude that in this range of initial shock pressures, the initiation occurs at localized centers from which the reaction spreads. Before we can be sure that the hot-spot mechanism is the only mechanism for polycrystalline solids at higher shock pressures more information is needed in the higher range. In particular it will be necessary to develop an equation of state for solid explosives in which the temperature can be accurately defined. It remains a possibility in the higher range of pressures, between about 120 kilobars and the detonation pressure, that there may be competing processes going on. More or less homogeneous reaction may be taking place when the Hugoniot energy jump exceeds about 100 cal/gm, particularly if the activation energy can be decreased by compression as has been recently suggested by Teller (32). It also remains for future work to establish the details of the process of localized initiation of reaction near the threshold limits of shock pressures, that is, in the range of pressures below 40 kilobars for most solid military explosives.

ACKNOWLEDGMENTS

The authors wish to acknowledge the painstaking work of J. Schneider, whose careful preparation and execution of the explosive tests permitted the development of the refined measurements reported herein. This work was supported, in part, by the Atomic Energy Commission through the E. O. Lawrence Radiation Laboratory, Livermore, California.

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TABLE 1

The Explosives Studied,
Their State and Densities

	Explosive	State	Density, g/cm^3
1.	Composition B RDX/TNT/Wax; 59/40/1	Cast	1.71
2.	Composition B-3 RDX/TNT 60/40 (Mean RDX Particle size; 60-80 microns)	Cast	1.72
3.	Cyclotol RDX/TNT; 75/25	Cast	1.73
4.	Trinitrotoluene (TNT) (Microcrystalline)	Cast	1.58 1.62
5.	Trinitrotoluene (Mean Particle Size; 40-80 microns)	Pressed	1.51 1.61 1.64

TABLE 2

Experimental Constants for Equation 1;
(U and u in mm/microsecond)

Material	ρo	a	b	c
Naval Brass	8.37	3.560	1.833	0
Plexiglas	1.18	2.710	1.568	-0.037
Lucite[1]	1.19	2.588	1.51	
TNT	1.60-1.62	2.39	2.05	0
TNT (liquid)[2]	1.472	2.00	1.68	0
Composition B B-3	1.72	2.71	1.86	0

1. Reference 12
2. Reference 30

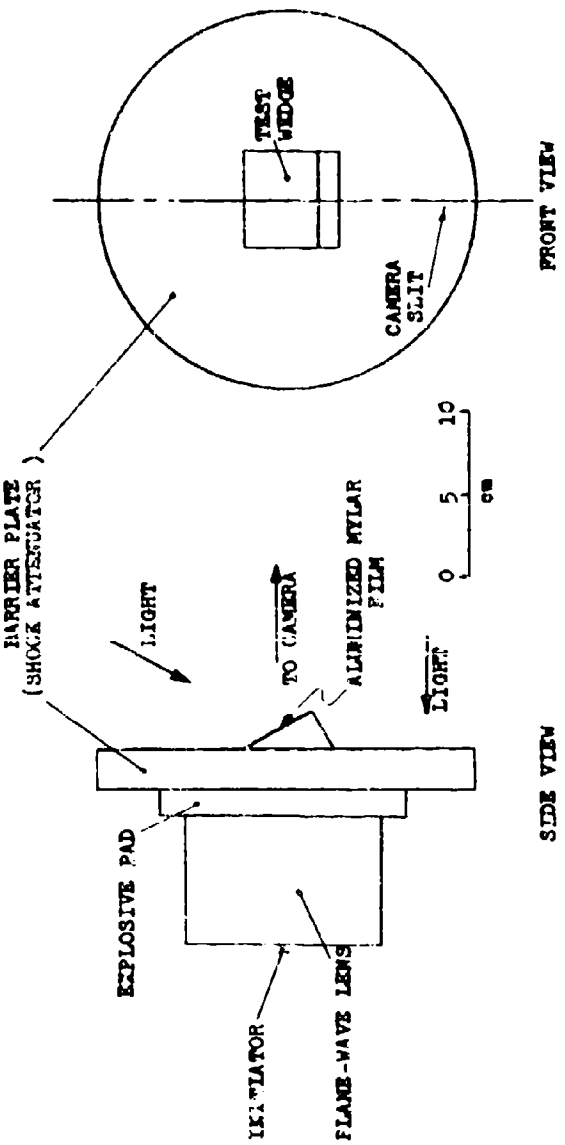

FIGURE 1 WEDGE-TEST ARRANGEMENT

FIG. 2 TYPICAL NOL WEDGE-TEST RECORD

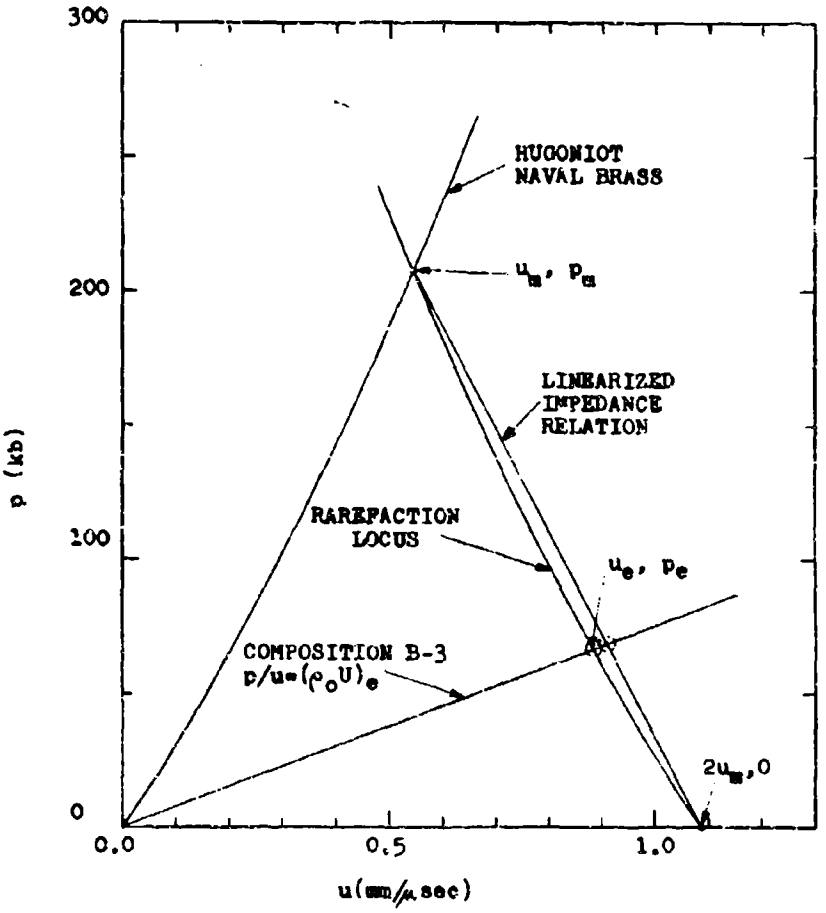

FIGURE 3 PRESSURE-PARTICLE VELOCITY DIAGRAM FOR DETERMINING SHOCK PRESSURE IN THE EXPLOSIVE

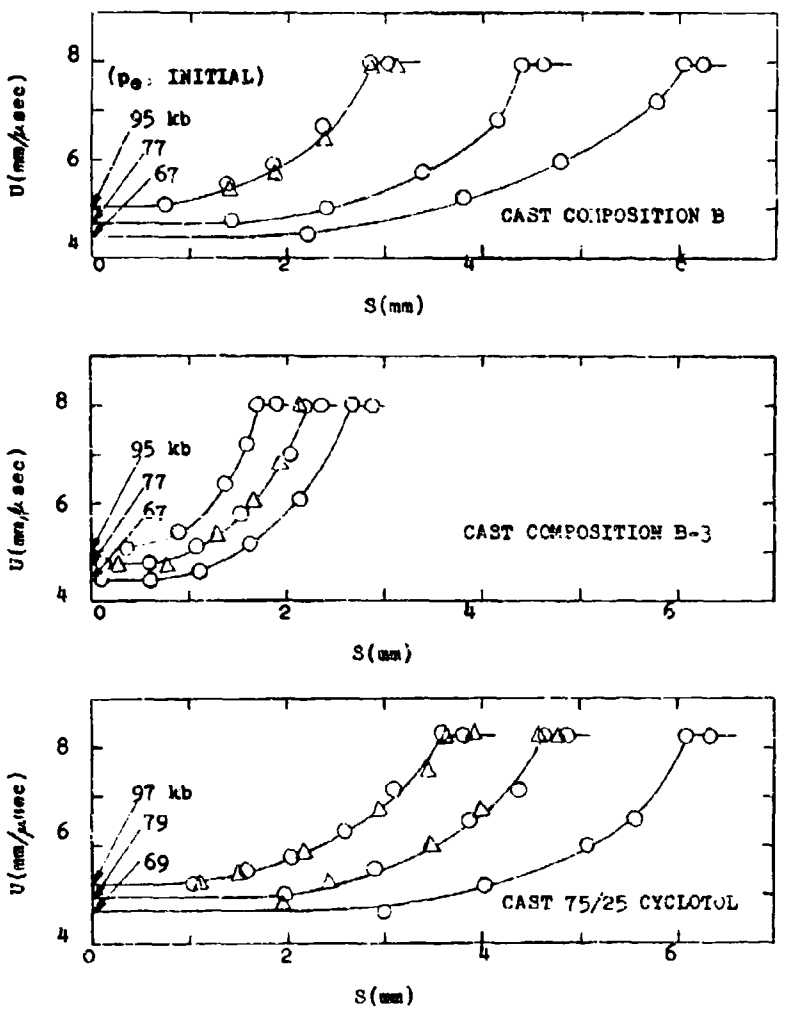

FIGURE 4 SHOCK VELOCITY VS DISTANCE FOR THREE CYCLOTOLS (FOR EACH SET OF CURVES, READING FROM LEFT TO RIGHT, THE BRASS ATTENUATOR THICKNESS WAS 0.5, 1.0, AND 1.5 INCHES)

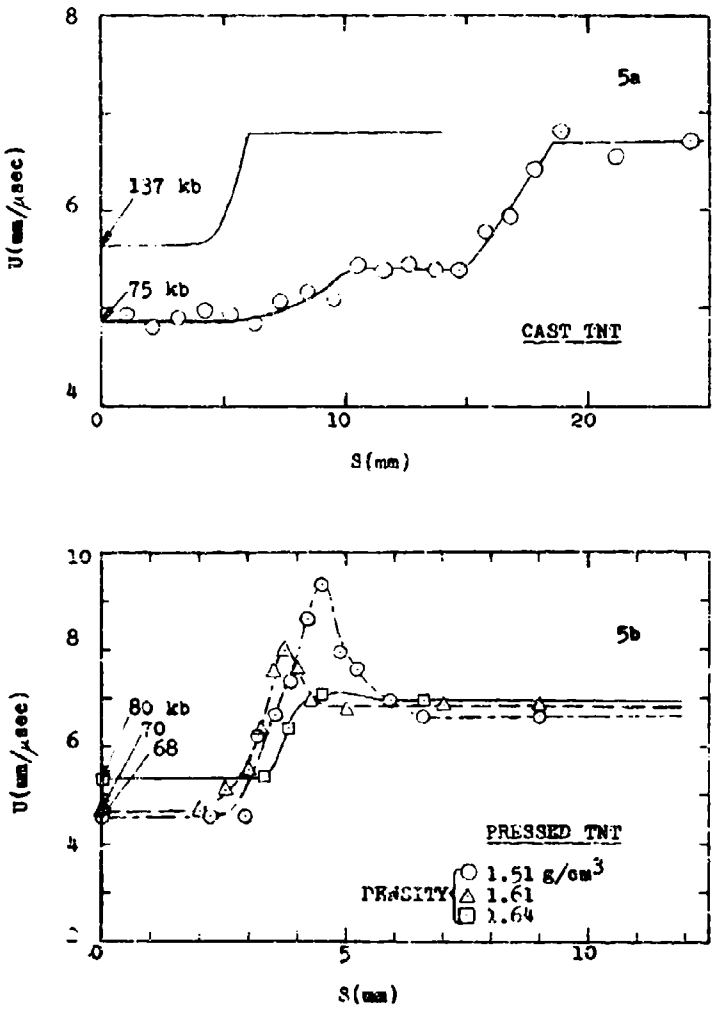

FIGURE 5 SHOCK VELOCITY VS DISTANCE FOR SEVERAL TNT CHARGES

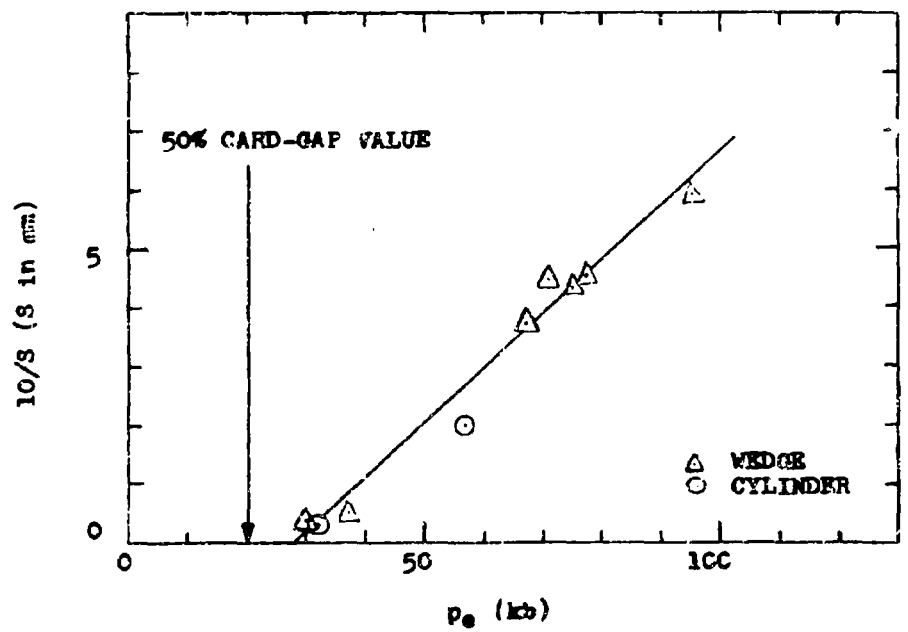

FIGURE 6 EFFECT OF INPUT PRESSURE (p_e) ON DISTANCE (S)-TO-STEADY-STATE DETONATION IN CAST COMPOSITION B-3

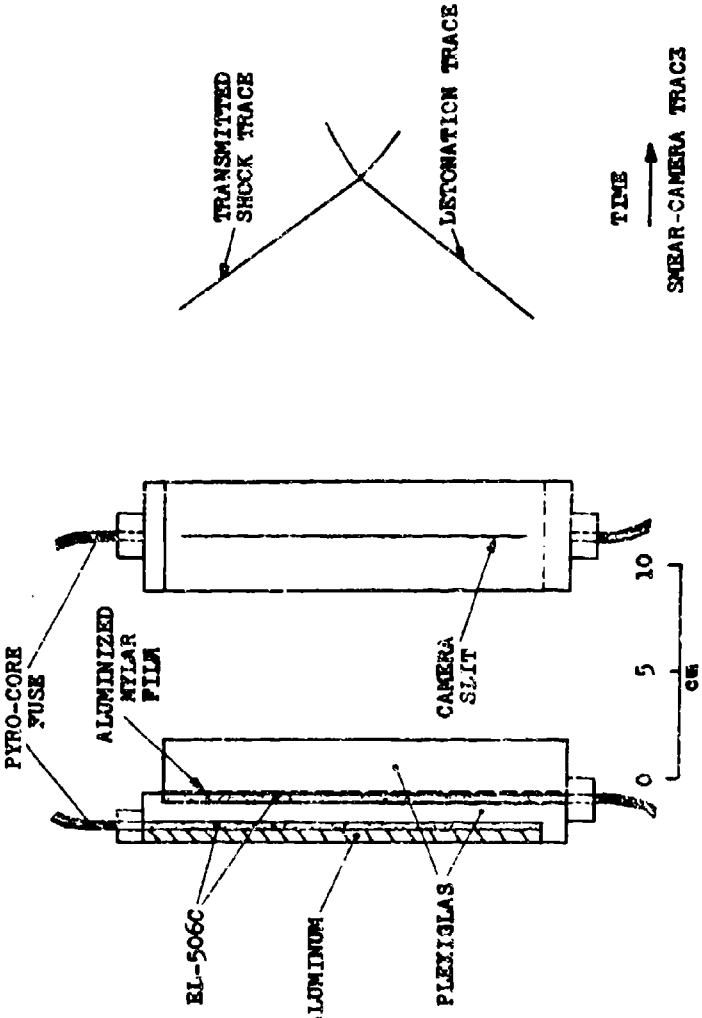

FIGURE 7 EXPERIMENTAL SET-UP FOR DETONATION QUENCHING BY PRESHOCK AND SKETCH OF SMEAR-CAMERA TRACE

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Initiation	INTI	Pressure	PRES	Shaped	SHAP
Detonation	DETO	Time	TIME		
Explosives	EXPL	Transition	TRNI		
Solid	SOLI	Peak	PKNG		
Cast	CAST	Amplitude	AMPI		
Pressed	PRSG	Velocity	VELC		
TNT	TNTE	Safety	SAFE		
Cyclotols	CYCT	Handling	HANL		
Composition B	COPB	Charges	CHAR		
RDX	RDXE	Polycrystalline	POYC		
Wax	WAXE	Equations	EQUA		

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